NASA / FAA eVTOL Crashworthiness Virtual Meeting

April 7th 2020

Justin Littell Ph.D.
NASA Langley Research Center
Structural Dynamics Branch

Why another eVTOL workshop/meeting?

- Intended to be specific to occupant protection and vehicle crashworthiness with specific application to eVTOL vehicle designs
  – Other system have their respective conferences and/or working groups
- Other similar have addressed crashworthiness/occupant safety
  – ASTM F44 eVTOL workshop / UAM working group
  – VFS Defining challenges
  – VFS Transformative Vertical Flight
- Today will be mainly an **introduction** to familiarize the UAM community to the concepts of vehicle crashworthiness from both a historical perspective but also how it can apply to eVTOL vehicle designs.
- A full day in-person workshop is still being planned at NASA LaRC tentatively Fall 2020. See https://nari.arc.nasa.gov/crashworthiness for details

Agenda – Webinar April 7th, 2020

- Welcome – Justin Littell / NASA
- Introduce the concept of crashworthiness from a historical perspective – Joseph Pellettiere / FAA
- Introduce a series of case studies that capture crashworthiness themes – Amanda Taylor / FAA
- Introduce potential paths toward certification regarding crashworthiness – Robert Stegeman / FAA

- Virtual meeting expected to last 1-1.5 hours.

Meeting Etiquette

- Stay on mute so that crosstalk/feedback/background noise is minimized. Speakers will be only ones talking
- Questions can be submitted through the comment section of the zoom meeting - please write down your question in the comment section. **Questions will not be answered during the presentations**, but collected/recorded and addressed at the in-person workshop later this year

- Other specific questions can be directed toward
  - Justin Littell – Justin.D.Littell@nasa.gov
  - Joseph Pellettiere – Joseph.Pellettiere@faa.gov

Introduction to Crashworthiness

Presented to: UAM Crashworthiness Workshop

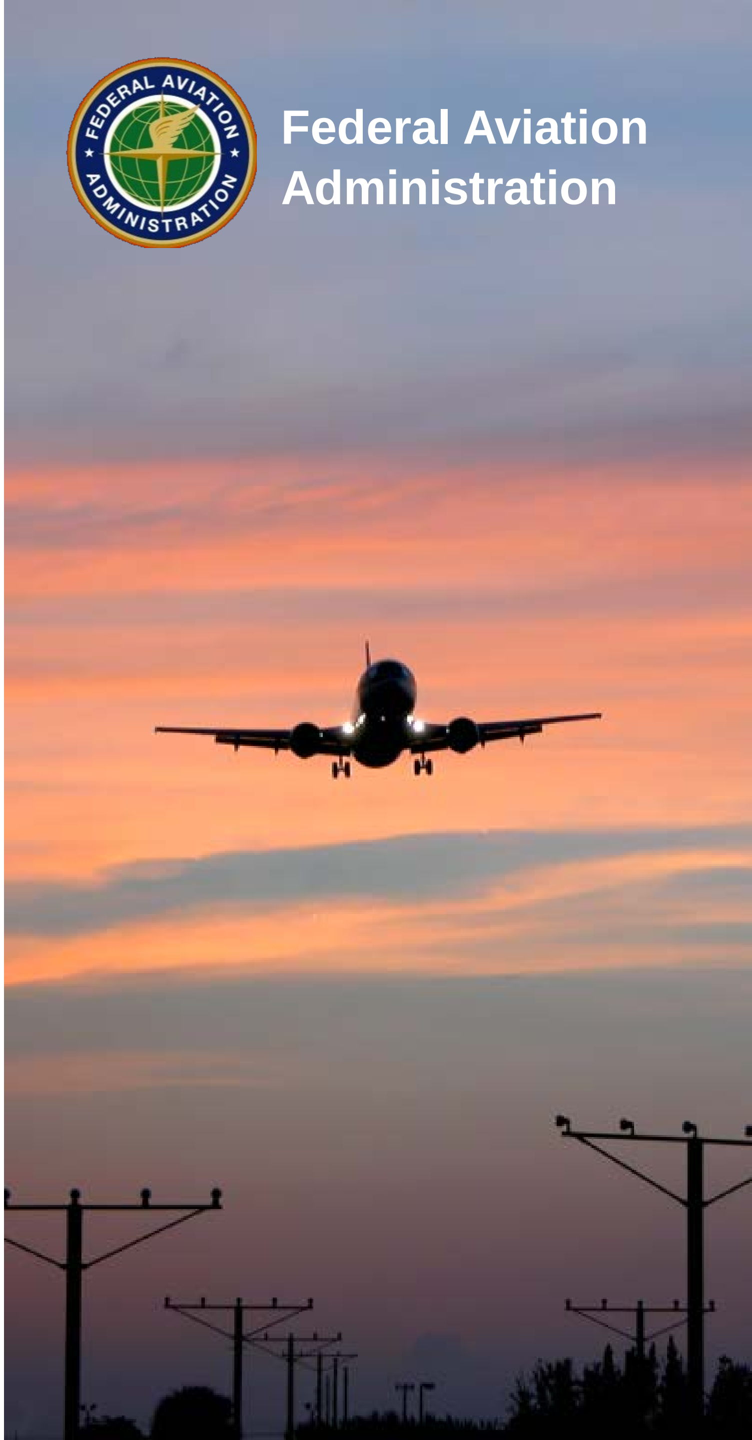
By: Joseph A. Pellettiere, Chief Scientific and Technical Advisor for Crash Dynamics

Amanda Taylor, Biodynamic Research Engineer, Civil Aerospace Medical Institute

Bob Stegeman

Small Airplane Standards Branch

Date: April 2020



Agenda

- Survivable crash
- What is crashworthiness
- Regulation history
- Physics of Impact
- Examples
- Current eVtol certification approach
- Future workshop

Miscellaneous Accident Facts

Thermal/fire injuries account for approximately 50% of fatalities

Impact injuries (trauma) account for approximately 50% of fatalities

Vast majority of accidents occur during the takeoff and landing phases

Takeoffs result in more severe fire accidents

Definition of a Survivable Accident

Survivable Accident: Survivable volume, restrained occupants, acceptable acceleration limits (injuries due to trauma not thermal/fire).

Most accidents are survivable.

Possible Crash Scenarios

CANDIDATE CRASH SCENARIO	IMPACT CONDITIONS	ACCIDENT TYPE	TERRAIN	HAZARD
GROUND-TO-GROUND, OVERRUN	LOW SINK SPEED LOW FORWARD VELOCITY SYM. A/P ATTITUDE GEARS EXTENDED	TAKEOFF ABORT LANDING OVERRUN	RUNWAY HARD GROUND	DITCH MOUND SLOPE SLAB LIGHT STANCHION
AIR-TO-GROUND HARD LANDING	HIGH SINK SPEED AND LANDING VELOCITY SYM. A/P ATTITUDE GEARS EXTENDED	HARD LANDING UNDERSHOOT	RUNWAY HARD GROUND	NONE
AIR-TO-GROUND IMPACT	HIGH SINK SPEED AND LANDING VELOCITY UNSYM. A/P ATTITUDE GEARS EXTENDED/RET	UNCONT/CONT GRD COLLISION STALL UNDERSHOOT	WOODED HILLY	TREES SLOPES BLDGS

Survivable Accidents Occur

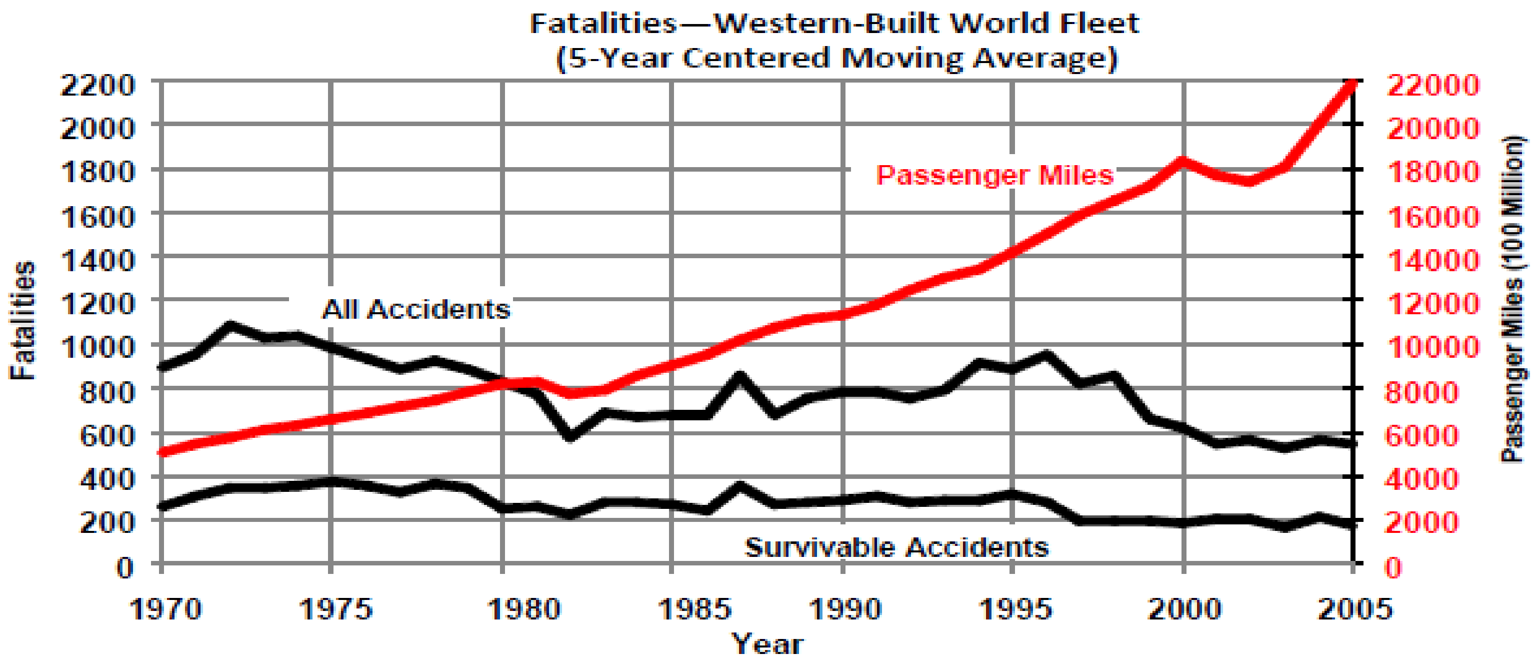


Figure 8. Number of Fatalities—All Accidents and Survivable Accidents—World Fleet

Survivable Crash Events

- Metal airframe with crushable space
  - Absorb primary impact energy
- Current seat designs
  - Protect occupant
  - Minimize secondary impact
- Cabin interior
  - Minimize secondary impact such as luggage bins
- Provide adequate exits
  - Need structural integrity

July 2013 – Asiana Flt 214
(777 - 3 fatal, 49 of 187 serious inj/307)

February 2009 – Turkish Flt 1951
(737-800 9 fatal, 25 severe inj/125)

2019 FAA Triennial Fire and Cabin Safety Research Conference

- Crashworthiness needs to be a primary design consideration instead of a last resort
- Instead of focus on seat, need multiple features that create a system for occupant protection
- Must consider certification cost verses safety benefits to get the best overall system
- Level of precision and confidence in certification requirements directly related to –
    - Risk allowances
    - Cost
    - Safety continuum
- One size doesn't actually fit all

What is Crashworthiness?

Crashworthiness is the ability of a structure to protect its occupants during an impact.

A crashworthy aircraft/rotorcraft is capable of:

- Limiting the loads transmitted to the occupants to survivable and/or non-injurious, humanly-tolerable levels (for a "survivable" impact).
- Providing a protective cabin surrounding the occupants.
- Providing a secure tie down of the occupants through the use of seats, restraint systems, seat track, and floor.
- Eliminating post-crash fire hazards and providing for emergency egress.
- Mitigating head strike potential by using pre-tensioned restraint systems or cockpit air bags.

Aircraft Crashworthiness
The Beginning

- **Hugh DeHaven** – considered by many to be the father of aircraft crashworthiness, developed the first systematic statement of the principles of crashworthiness.
- Packaging principles of light aircraft design - 1952

DeHaven’s Four Principles

- The package should not open up and spill its contents, and should not collapse under expected conditions of force.
- The packaging structures which shield the inner container must not be made of brittle or frail materials; they should resist force by yielding and absorbing energy.
- Articles contained in the package should be held and immobilized. This interior packaging is an extremely important part of the overall design, for it prevents movement and the resultant damage from impact against the inside of the package itself.
- The means for holding an object inside a shipping container must transmit the forces applied to the container to the strongest parts of the contained objects.

Current Crashworthiness Philosophy

CREEP

Container – The fuselage's resistance to structural collapse, and the survivable volume in occupied spaces.

Restraint – The ability of seat belts and seats to help passengers survive the sudden force of deceleration during impact.

Environment – The cabin interior design must minimize the potential for injury during a crash (i.e. overhead bins do not collapse onto passengers).

Energy Absorption – The fuselage should provide energy absorption through controlled deformation.

Postcrash factors – Occupants must be able to perform post crash actions (i.e. evacuation).

Container

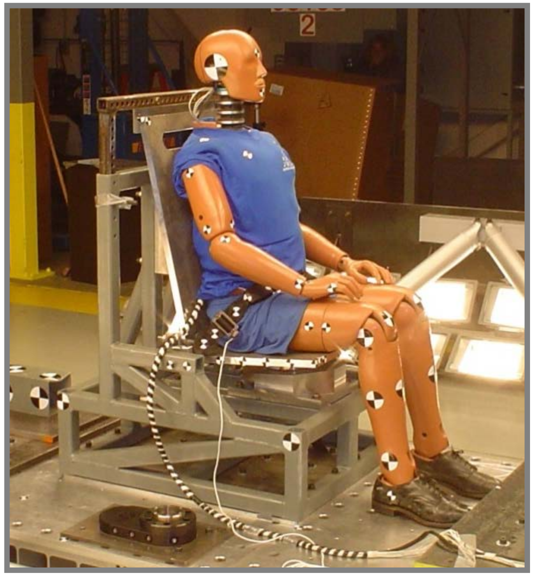
Maintain Survivable Volume

Seat Restraint Systems

Dynamic requirements:

14 CFR 23.562, 25.562, 27.562, 29.562

- Lumbar load limits
- Head injury criteria
- Seat belt load limits



Environment

Protect against secondary impacts

Energy Management

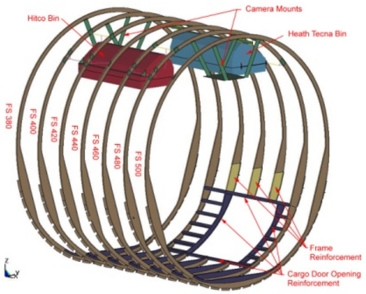
Energy absorbing structures

Landing gear

Fuselage

- Frames
- Keel beams
- Stanchions
- Floor beams

Stanchions



Seats

- Energy absorbing – passive design
- Stroking – active design
- Energy absorbing seat pan design

Nonstructural

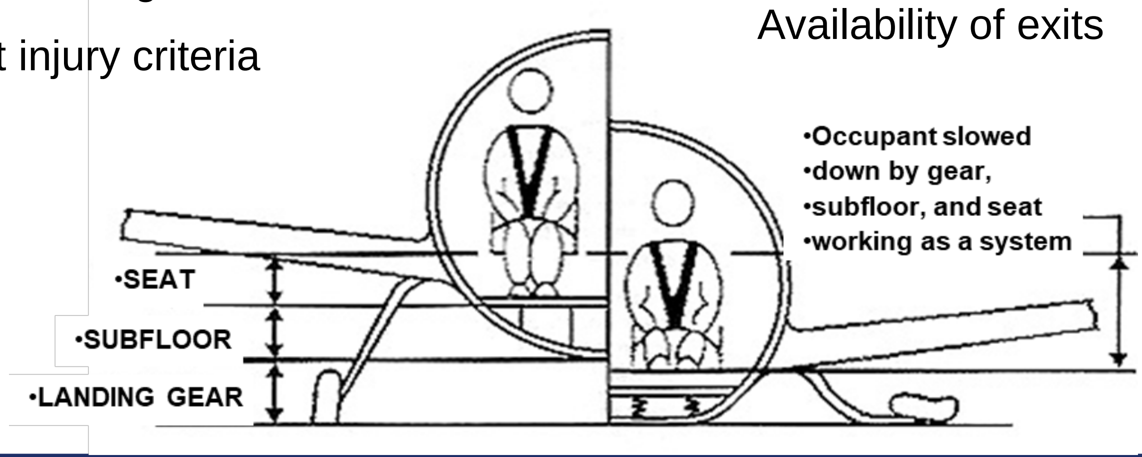
- Inflatable
  - Parachute

Postcrash

Evacuation
- Exits
- Aisle way lighting
- Slides
- Life rafts

Elements of Crashworthy Aircraft System Design

- Airframe structure
  - Strength
  - Impact attenuation
- Aircraft seats
  - Strength
  - Energy absorbing
  - Occupant injury criteria
- Interior furnishings
  - Overhead bins
- Post crash fire
  - Fuel containment
    - CRFS
- Emergency evacuation
  - Availability of exits



History of the Standards

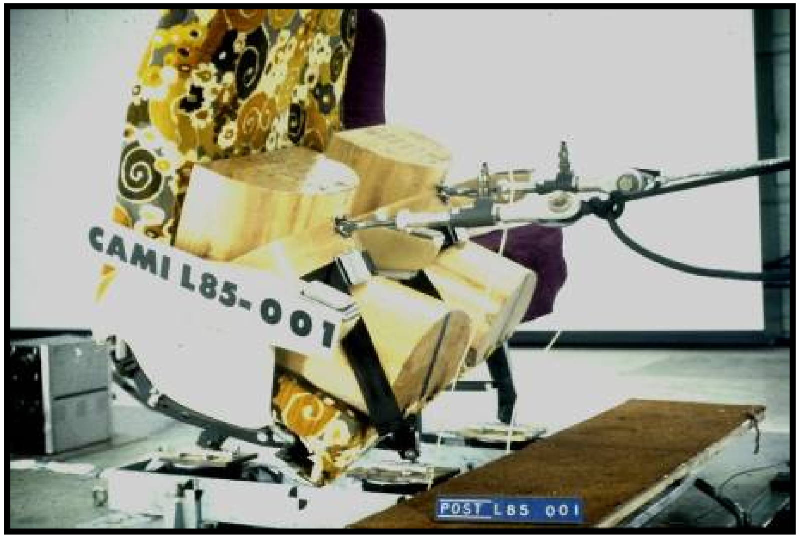
- **Original requirements focused on seat and restraint system strength**
- **Static test requirements were essentially the same since 1958**
  - **Title 14, Section 561 of Parts 23,25,27 and 29: Emergency Landing Conditions, General.**
  - **TSO C39b: Aircraft Seats and Berths (cites NAS 809)**
  - **TSO C22f: Safety Belts (cites NAS 802)**

Ah, the good old days. In the 1920s, the preflight safety briefing consisted of a pilot strapping a parachute onto his passenger. (Nathaniel L. Dewell/NASM)

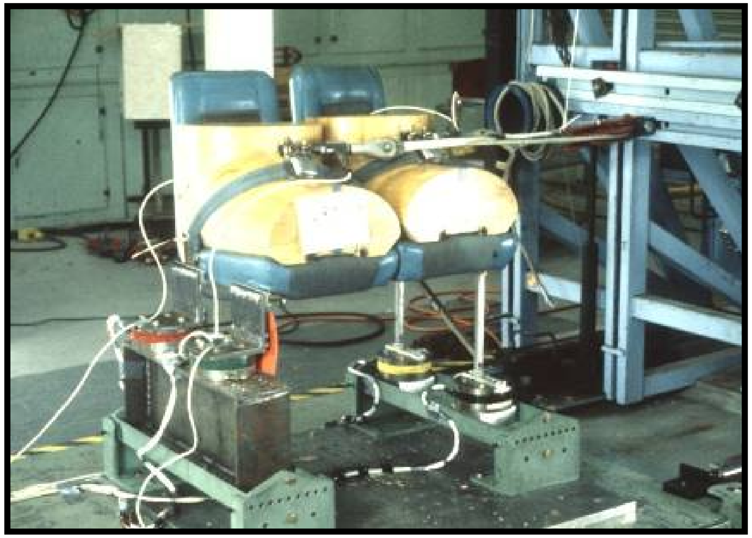
History of the Standards

Loads applied slowly with wooden blocks in multiple directions. Does not apply forces in the same way an actual occupant would

Forward Static Test

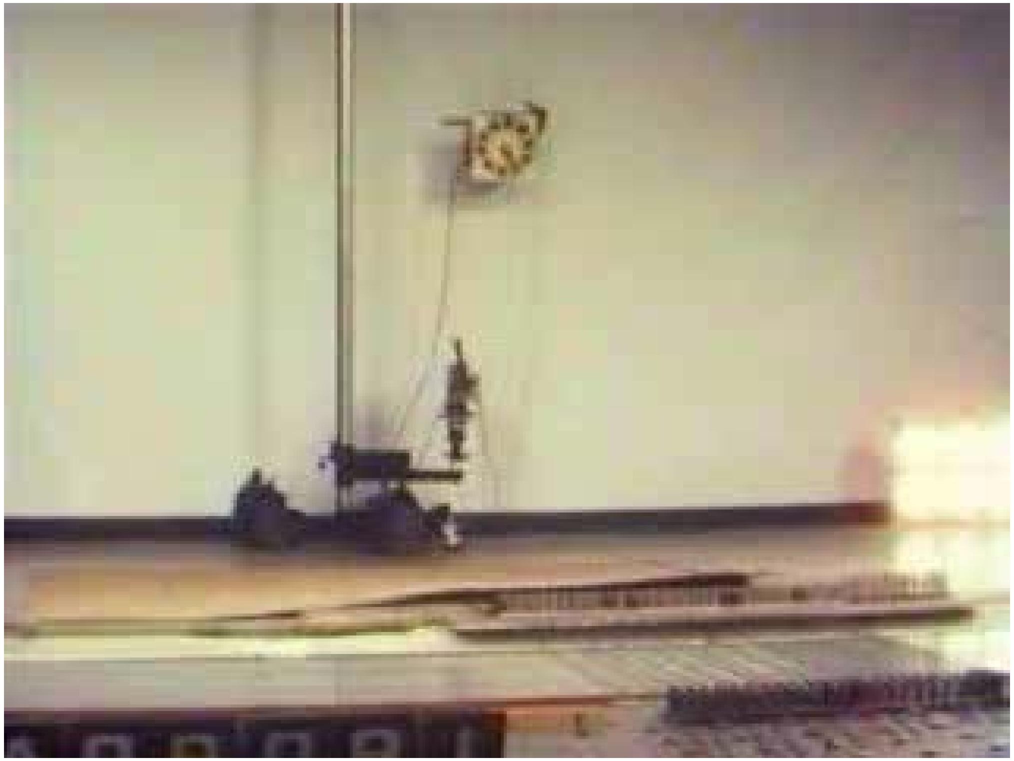


Lateral Static



History of the Standards

Dynamic testing revealed serious problems with seats that met the static test standards



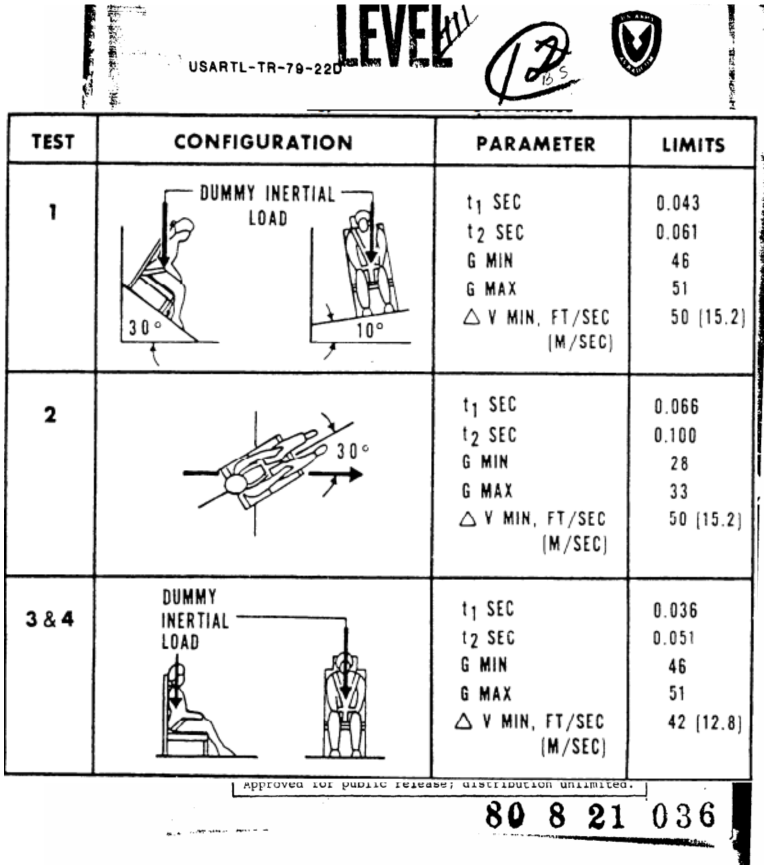
Development of Standards

- **The General Aviation Safety Panel (GASP) was Instrumental in Formulating Dynamic Performance Standards**
- **Represented a broad constituency from the General Aviation Community**
- **Objectives**
  - Analyze Results of Existing Crash Dynamics Research
  - Develop Crash Dynamics Design Standards

A 1979 photo by Brian Smith of the wreck of Cessna 172 N734YH at the end of Maguire's Runway 18

Development of Standards

- **The Development and Application of Crash Dynamics Technology Fostered the Dynamic Performance Standards**
- **US Army's Aircraft Crash Survival Design Guide**
  - Hughes AH-64A Apache
  - Sikorsky UH-60A Blackhawk
- **FAA/NASA Crash Dynamics Research**


USARTL-TR-79-22D LEVEL III

TEST	CONFIGURATION	PARAMETER	LIMITS
1	DUMMY INERTIAL LOAD; 30°; 10°	t_1 SEC t_2 SEC G MIN G MAX Δ V MIN, FT/SEC (M/SEC)	0.043 0.061 46 51 50 (15.2)
2	30°	t_1 SEC t_2 SEC G MIN G MAX Δ V MIN, FT/SEC (M/SEC)	0.066 0.100 28 33 50 (15.2)
3 & 4	DUMMY INERTIAL LOAD	t_1 SEC t_2 SEC G MIN G MAX Δ V MIN, FT/SEC (M/SEC)	0.036 0.051 46 51 42 (12.8)

Approved for public release; distribution unlimited.

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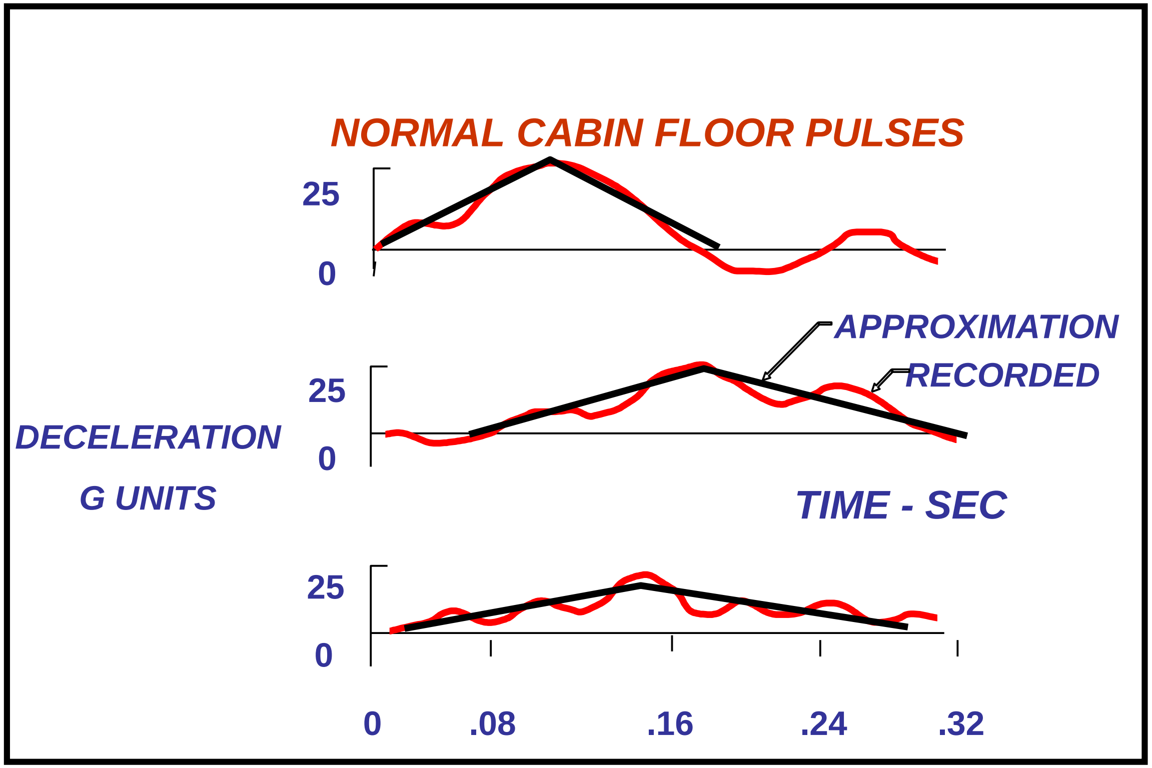
Development of Standards

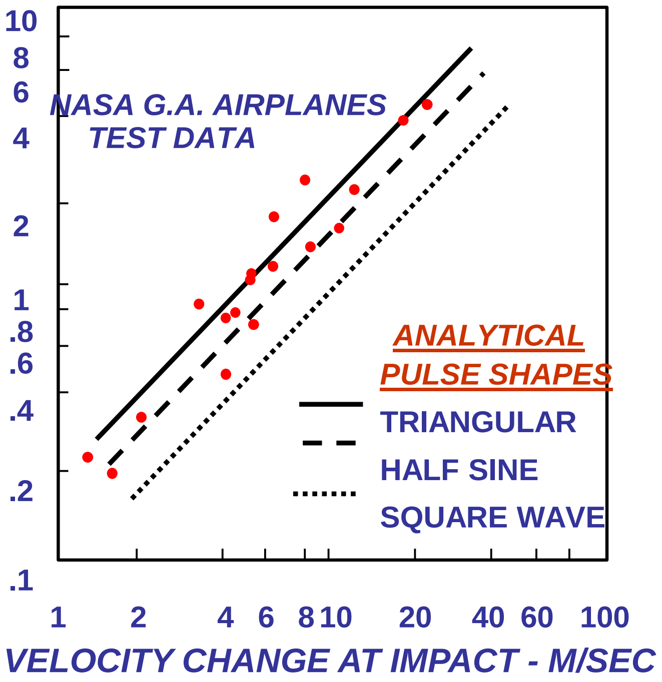
New standards for small aircraft were developed based on full-scale fuselage impact tests.

- **vertical drop tests**
- **combined horizontal / vertical impact t**

Development of Standards

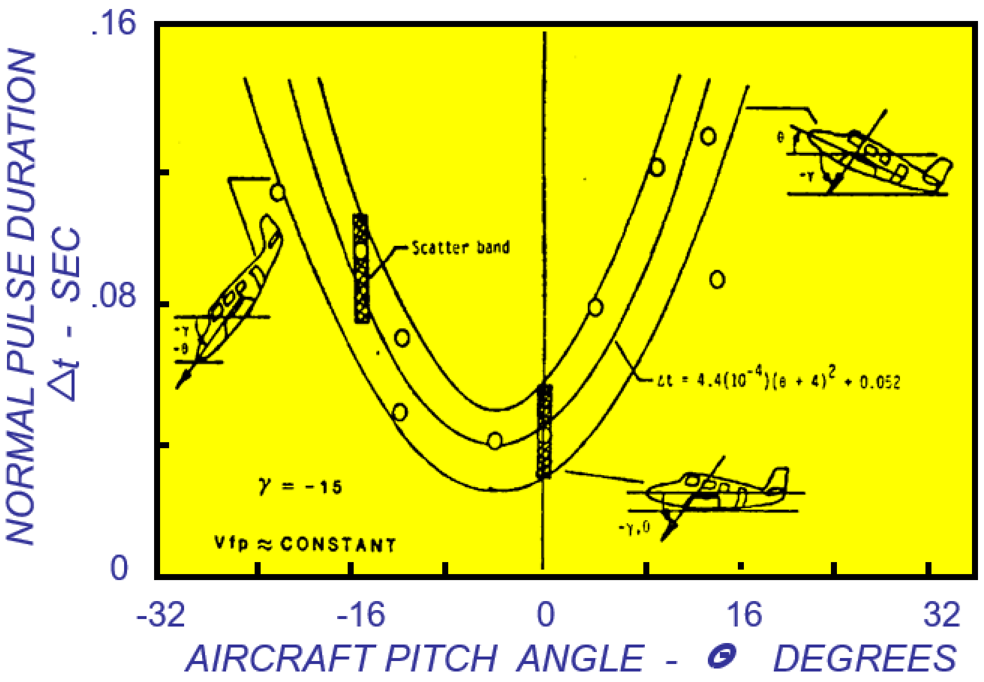
Example Time Histories

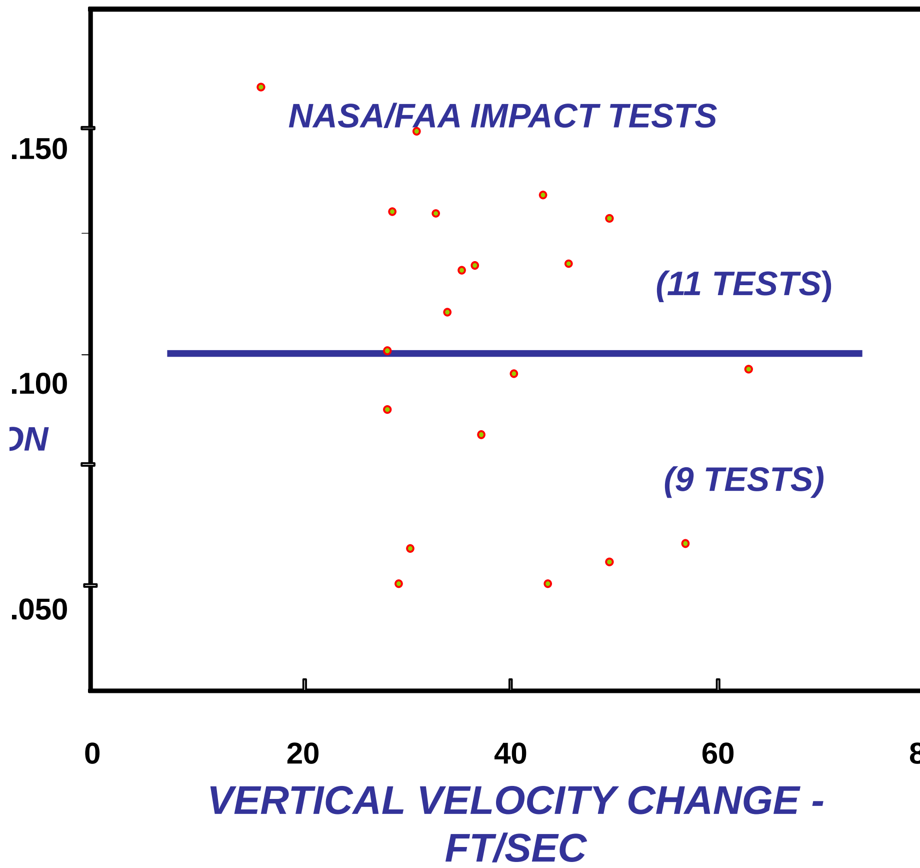




Development of Standards

Impact Pulse Duration as a
Function of Impact Attitude



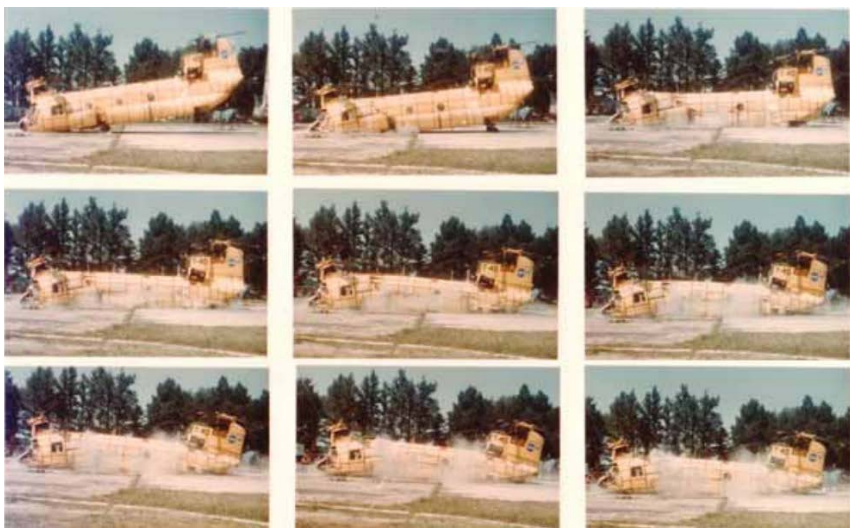


GASP Established a Pass/Fail Performance Criteria

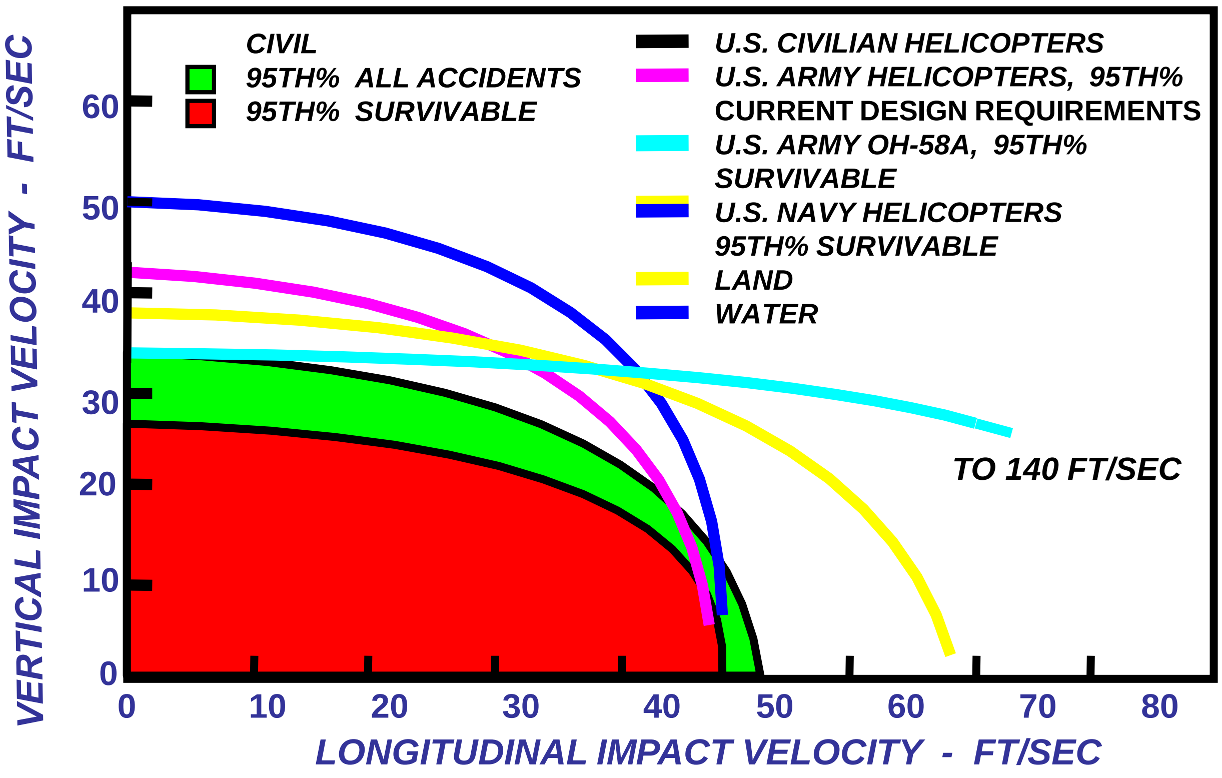
- **Performance Criteria Relates Selected Measured Dynamic Test Parameters to Injury Criteria**
- **Performance Criteria Evaluates the Seat/ Restraint System's Potential for Preventing or Minimizing Injuries from:**
  – Primary Impacts
  – Secondary Impacts
  – Occupant Skeletal Loads

Development of Standards

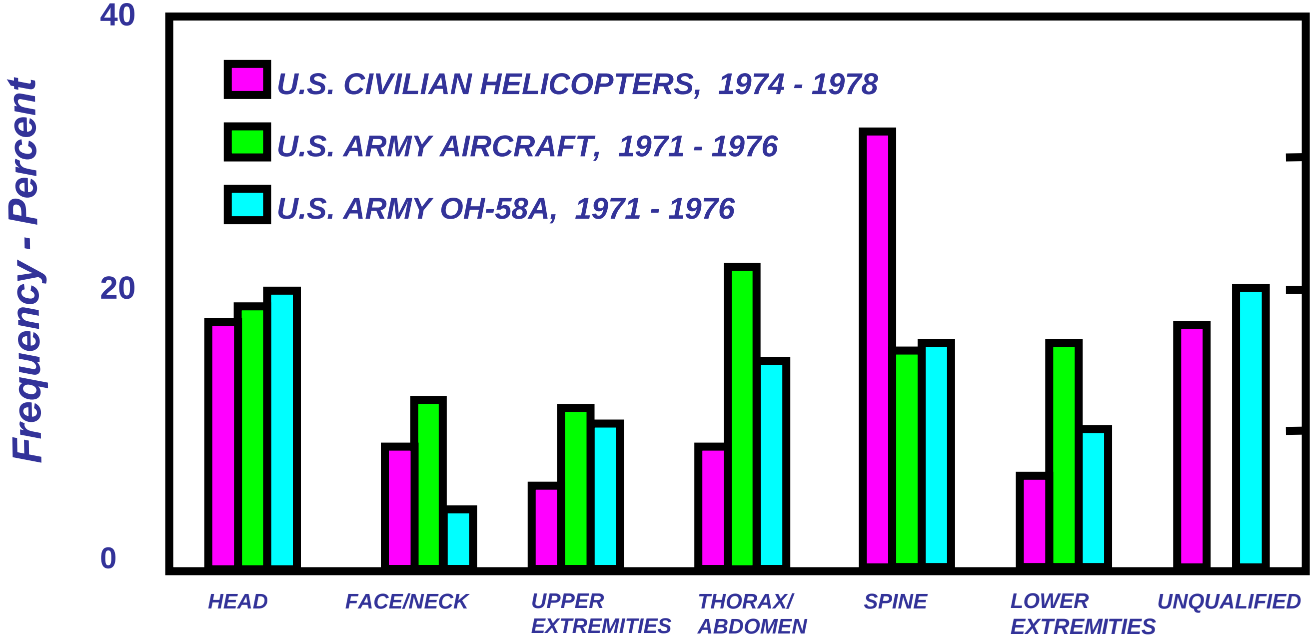
- New standards for rotorcraft were based primarily on analysis of accident data.
- Large data base available from the military



Development of Standards

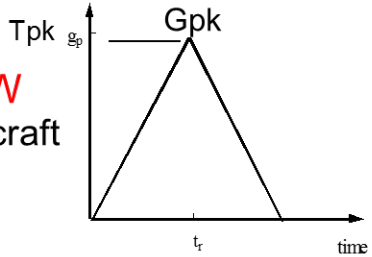


Development of Standards



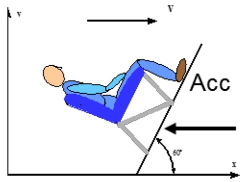
Frequency Of Major And Fatal Injuries To Each Body Region As Percentages Of Total Major And Fatal Injuries In Survivable Accidents

Seat Safety Standards



Requirements for NEW
- General Aviation Aircraft
- Transport Aircraft
- Rotorcraft

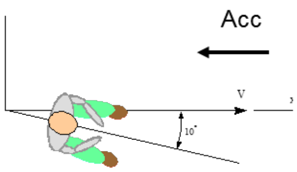
Test-1 Condition



From Right Side

Combined Vertical Horizontal Orientation	Small Airplanes (Part 23)		Transport (Part 25)	Rotorcraft (Part 27)
	Pilot	Passenger		
Gpk (gs)	19	15	14	30
Impact Velocity (f/s)	31	31	35	30
Onset Time (Tpk)	0.05	0.06	0.08	0.03

Test-2 Condition



From Above

Horizontal 10º Yaw Orientation	Small Airplanes (Part 23)		Transport (Part 25)	Rotorcraft (Part 27)
	Pilot	Passenger		
Gpk (gs)	26	21	16	18.4
Impact Velocity (f/s)	42	42	44	42
Onset Time (Tpk)	0.06	0.08	0.09	0.07

Seat Safety Standards

- **Dynamic test requirements were adopted in 1988 for Parts 23 and 25, and 1989 for Parts 27 and 29**
- **These requirements were originally applicable to aircraft designed after the effective date, not to ones already in design or production.**
- **The requirements have also been partially implemented on some new derivative aircraft.**

Historical Summary

- Current transport standards were quickly implemented by industry
- Survivability with conventional designs has shown good crashworthiness performance
- General aviation and rotorcraft are lagging due to adoption rate
- Newly designed aircraft can start anew and maintain the safety performance

Current Standards and Case Studies

Federal Aviation Administration

eVTOL Crashworthiness Workshop

By: Amanda Taylor

Biomedical Research Engineer

Civil Aerospace Medical Institute

Date: April 7, 2020

The Physics of Impact

Large horizontal velocity change over a relatively long period of time

The Physics of Impact

Small vertical velocity change and a moderate horizontal velocity change over a short time period

NASA aircraft crash test #21
NASA Langley Research Center 6/10/1981 Image # EL-2001-00465

The Physics of Impact

Small vertical velocity change over a very short time period

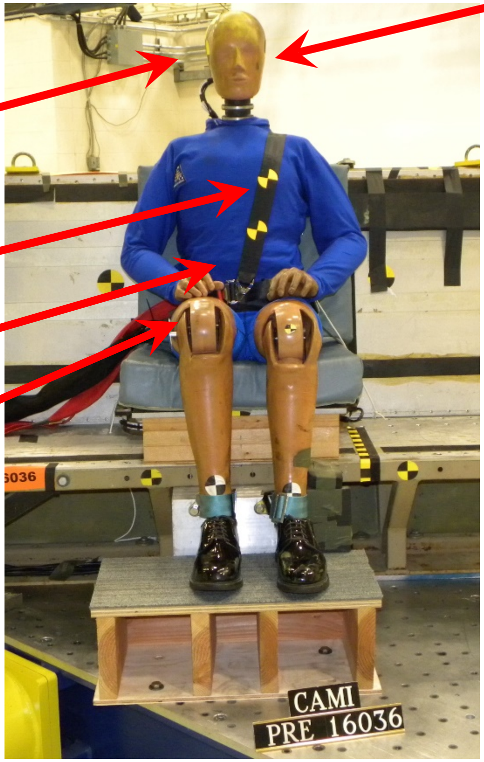
Integral Seats– Test 1

Combined Vertical Horizontal Orientation	Rotorcraft (Part 27/29)
Peak G (gs)	30
Impact Velocity (ft/s)	30
Onset Time	30 ms

Injury/Pass-Fail Criteria

$$HIC = \left[(t_2 - t_1) \left\{ \frac{1}{(t_2 - t_1)} \int_{t1}^{t2} a(t)dt \right\}^{2.5} \right]_{max}$$

Parameter	Injury Criteria
Head Injury Criteria (HIC)	1000
Shoulder Harness loads	1750 lb. (single) 2000 lb. (dual)
Lumbar Load Fz	1500 lb.
Femur Load (axial)*	2250 lb.



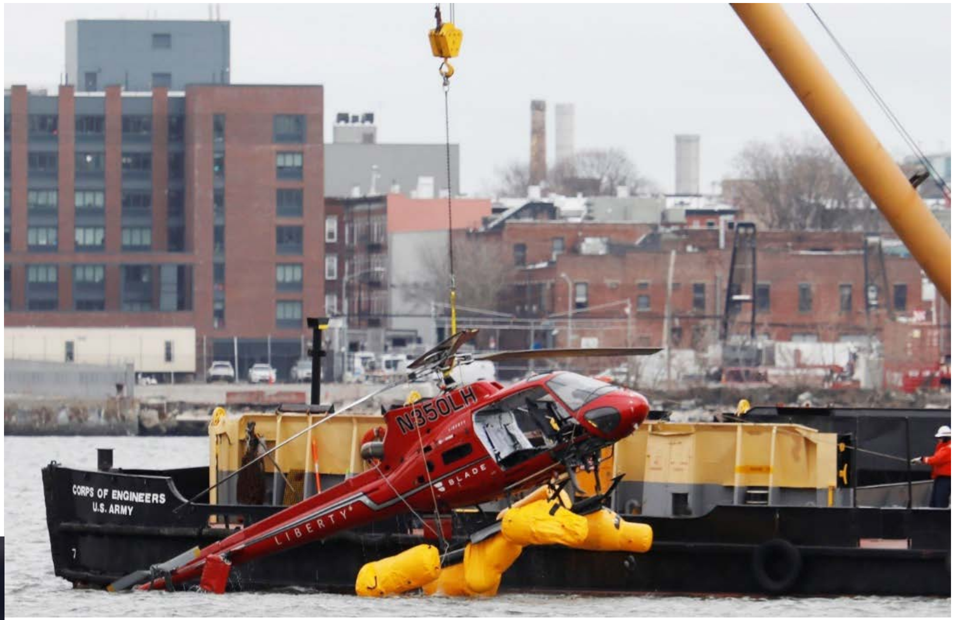
Specified in Part 23.562, 25.562, 27.562, and 29.562

Measured for Part 572 Subpart B (Hybrid II)

* (part 25 only)

Case Study – Unintended Use Fly Nyon

- **ERA18MA099**
- **March 11, 2018**
- **5 Fatal**
- **1 Minor**



AS 350 B3E

Case Study Fly Nyon

Case Study – Post Crash Fire

- **CHI15MA290**
- **July 3, 2015**
- **1 Fatal**
- **2 Serious**

AS 350 B3E

Case Study – Fully Crashworthy Aircraft

- **ERA16LA124**
- **3/05/2016**
- **2 None**

Cirrus SR22

Case Study – Fully Crashworthy Aircraft

- **CHI06FA245**
- **8/28/2006**
- **1 Fatal**
- **3 Serious**

Cirrus SR22

Case Study – Child Restraints

- **CEN17FA067**
- **January 4, 2017**
- **1 Fatal**
- **1 Serious**
- **1 None**

Experimental Bede BD-4

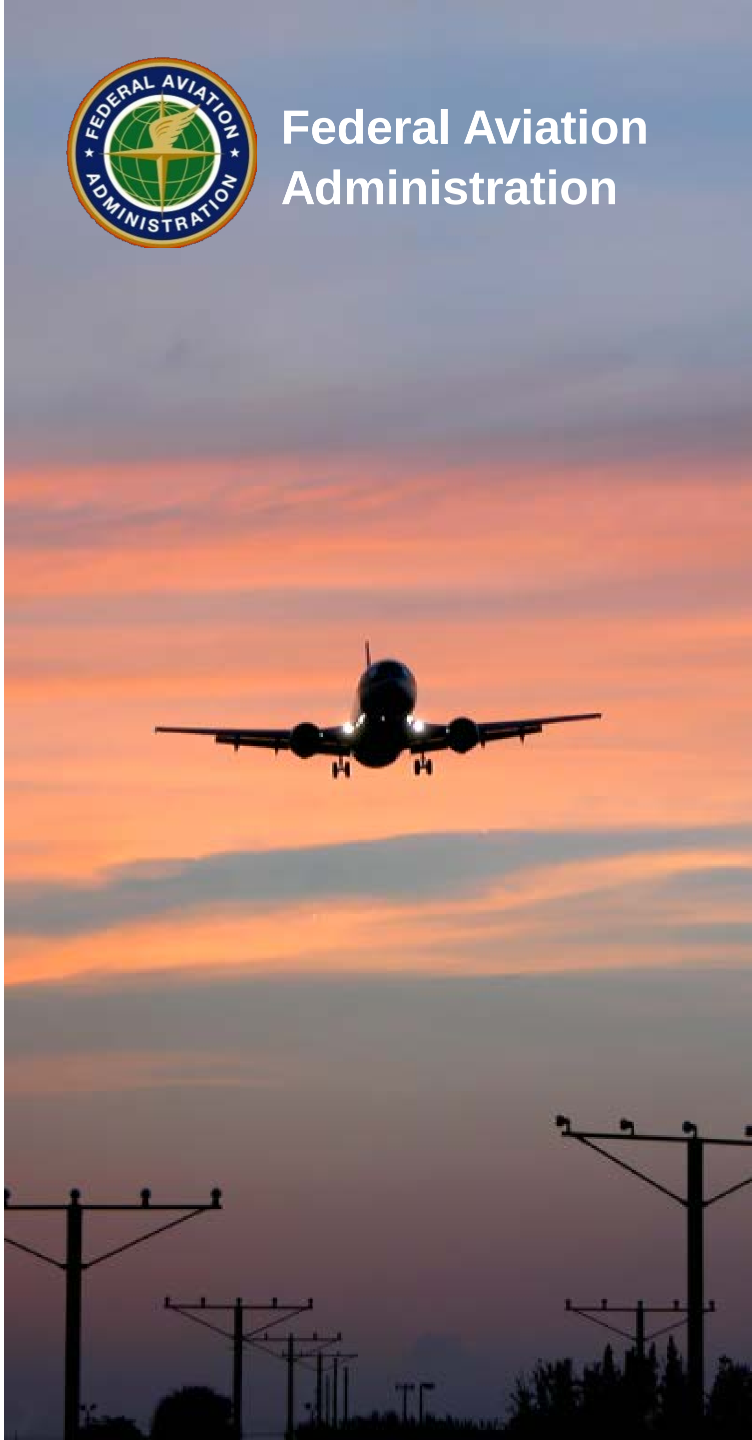
Case Study – Child Restraints

Crashworthiness Innovations

EMAS – Engineered Material Arresting System

Deployable Energy Absorber

Possible eVtol Certification Approach



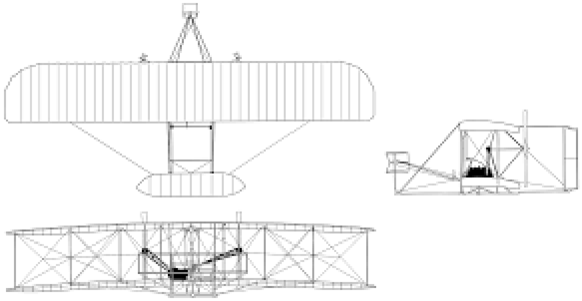
Presented to: UAM Crashworthiness Workshop

By: Bob Stegeman

Small Airplane Standards Branch

Date: April 2020

EVTOL Certification-First Steps



- Define the aircraft configuration
- Define the aircraft utilization
- Determine standards staff based upon configuration
- These aircraft don’t typically fit into the normal certification holes and require coordination for cert basis
- Certification basis made more difficult without fixed design

EVTOL Certification-Regulatory Framework

- **Framework for Certification has changed in past couple of years for part 23**
  - Performance based-broader rules
  - Prescriptive requirements in industry standards
- **Part 27 has not completed this change yet**
- **Old prescriptive methods are still utilized in both 23/27**
- **Hybridization of these methods for cert basis takes more time**
- **Much of crashworthiness not changed much since 1980s**

EVTOL Certification - Regulations + Vehicle

- **Define how vehicle operates/flies/ crashes**
- **How does it crash, based upon how it flies considering loss of power, thrust**
  - Vtol-has transient phase to horizontal or is purely vertical thrust-will drop like helo
  - Fixed wing/wingborne lift flight(can land horizontally)-will glide in like airplane
- **Determine cert basis**
  - Primarily part 23
  - Primarily part 27
  - Combination part 23/27 hybrid

EVTOL Certification-Methods of Compliance

After cert basis determined……

How do we demonstrate crashworthiness?

Early experiments in transportation

- **Test or analysis based upon test….**
  there will be testing…..
- **Some form of traditional dynamic/static option**
- **Longer/More Advanced/Likely Safer/But…More Expensive Paths**
  - Automotive path of full vehicle crash response/dummy restraint
  - Potentially extensive modelling that will likely require substantiation via large scale test
- **New avenues will be more of a challenge as vehicle type/operations certification is not stable**
- **Traditionally, Certification moves ahead incrementally**

EVTOL Certification-Current Example Static Loads

- **Conventional wisdom and current state of the art for a s/vtol plane with wingborne cruise**

Protection Requirement	**23.561 amd 23-62 23.562 amd 23-62**	**ASTM F3083 Level 2 Aircraft**	**27.561 amd 27-32 27.562 amd 27-25**
Static Occupant			
Forward	9.0g	9.0g	**16g**
Rearward	-	-	**1.5g**
Upward	3.0g	3.0g	**4g**
Downward	6.0g	6.0g	**20g after intended displacement of seat device**
Sideward	1.5g	1.5g	**8g**
Occupant weight		190 pounds	**170 pounds***
Static items of Mass			
Forward	18.0g	**18.0g**	12g
Rearward	-	-	**1.5g**
Upward	3.0g	**3.0g**	1.5g
Downward	-	-	**12g**
Sideward	4.5g	4.5g	**6g**
Retractable Gear Ultimate inertia force	3g	3g	-

*170 pounds is used as 190 pounds is traditionally used to accommodate parachute on utility and acrobat aircraft.

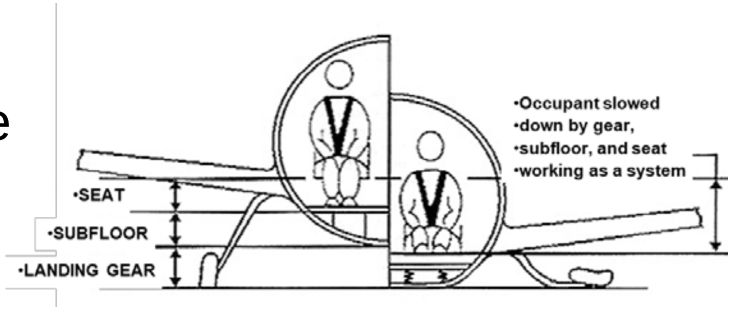
EVTOL Certification-Current Example Dynamic Loads

- **Conventional wisdom and current state of the art for a s/vtol plane with wingborne cruise**

Dynamic Occupant			
1st test (combined fwd/down) 1st row	19g, Δ velocity = 31 ft/sec, 0.05 sec rise time	19g, Δ velocity = 31 ft/sec, 0.05 sec rise time	**30g, Δ velocity = 30 ft/sec, 0.031 sec rise time (with floor warpage)**
1st test (combined fwd/down) Other rows	15g, Δ velocity = 31 ft/sec, 0.06 sec rise time	15g, Δ velocity = 31 ft/sec, 0.06 sec rise time	**30g, Δ velocity = 30 ft/sec, 0.031 sec rise time (with floor warpage)**
2nd test (FWD) with floor warpage 1st row	26g, Δ velocity = 42 ft/sec, 0.05 sec rise time	**26g, Δ velocity = 42 ft/sec, 0.05 sec rise time**	18.4g, Δ velocity = 42 ft/sec, 0.071 sec rise time
2nd test (FWD) with floor warpage Other rows	21g, Δ velocity = 42 ft/sec, 0.06 sec rise time	**21g, Δ velocity = 42 ft/sec, 0.06 sec rise time**	18.4g, Δ velocity = 42 ft/sec, 0.071 sec rise time ~~Same as above~~
ATD weight	170 pounds	170 pounds	170 pounds

EVTOL Certification-Best Practices

Advantageous to build crashworthiness features into airframe design



- Crushable, energy absorbing airframe
- More-rigid passenger cabin structure
- Anti plowing bulkheads/features
- Solid restraint/seat attachments to airframe, but can gimbal and stay attached in crash
- Consider headstrike/flail envelope in cabin avoid rigid, sharp features
- Restrain items of Mass/batteries/powerplants/cargo
- Ensure egress capability features after crash/deformation
- Minimize post crash fire hazards

Agenda for in-person workshop, Fall 2020

https://nari.arc.nasa.gov/crashworthiness

8:00 AM			*Coffee*
8:30 AM	NASA LaRC	Justin Littell	Welcome and Introduction to the Workshop
8:40 AM	NASA LaRC	Susan Gorton	NASA RVLT Project Overview
8:50 AM	VFS	Mike Hirschberg	*The Electric VTOL Revolution*
9:00 AM	FAA	Joseph Pellettiere	*Historical Basis for Crashworthiness and Occupant Safety*
9:30 AM	FAA CAMI	Amanda Taylor	*Current Seat Testing and Accident Case Studies*
10:00 AM	NASA LaRC	Jacob Putnam	*Certification by analysis - NASA F28 case study*
10:20 AM			Break
10:45 AM	NIAR	Gerardo Oliveras	*How simluation can aid in crashworthy design*
11:15 AM	NASA LaRC	Justin Littell	*NASA Crashworthiness research as basis for regulations*
11:30 AM	NAVAIR	Lindley Bark	DoD/NAVY Crashworthiness Approach
11:50 AM	USAARL	Joseph McEntire	Army Crashworthiness
12:10 PM	EASA	Aiko Duehne	*EASA VTOL SC*
12:30 PM			*Lunch*
1:00 PM	GAMA	Lowell Foster	*The Need for Alternative Crashworthiness Approaches for eVTOL*
1:30 PM	ASTM	Eric Nottorf	*ASTM F44 as Means of Compliance for Part 23*
2:00 PM	Uber	Ryan Naru	*Specifics of UAM Operations*
2:30 PM	FAA AIR	Bob Stegeman	*FAA Application of Crashworthiness Regulations for EVTOLS/UAM vehicles Part 1*
3:00 PM	FAA AIR	Bob Stegeman	*FAA Application of Crashworthiness Regulations for EVTOLS/UAM vehicles Part 2*
3:30 PM			Open discussion
4:00 PM			Open discussion
4:30 PM	NASA LaRC	Martin Annett	LandIR Tour
5:00 PM			ADJOURN